

Agronomic values of greenwaste biochar as a soil amendment

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Abstract. A pot trial was carried out to investigate the effect of biochar produced from greenwaste by pyrolysis on the yield of radish (*Raphanus sativus* var. Long Scarlet) and the soil quality of an Alfisol. Three rates of biochar (10, 50 and 100 t/ha) with and without additional nitrogen application (100 kg N/ha) were investigated. The soil used in the pot trial was a hardsetting Alfisol (Chromosol) (0–0.1 m) with a long history of cropping. In the absence of N fertiliser, application of biochar to the soil did not increase radish yield even at the highest rate of 100 t/ha. However, a significant biochar × nitrogen fertiliser interaction was observed, in that higher yield increases were observed with increasing rates of biochar application in the presence of N fertiliser, highlighting the role of biochar in improving N fertiliser use efficiency of the plant. For example, additional increase in DM of radish in the presence of N fertiliser varied from 95% in the nil biochar control to 266% in the 100 t/ha biochar-amended soils. A slight but significant reduction in dry matter production of radish was observed when biochar was applied at 10 t/ha but the cause is unclear and requires further investigation.

Significant changes in soil quality including increases in pH, organic carbon, and exchangeable cations as well as reduction in tensile strength were observed at higher rates of biochar application (>50 t/ha). Particularly interesting are the improvements in soil physical properties of this hardsetting soil in terms of reduction in tensile strength and increases in field capacity.

Additional keywords: charcoal, char, agrichar, soil strength, soil carbon sequestration, hardsetting soil, slow pyrolysis.

Introduction

Biochars refer to the high carbon materials produced from the slow pyrolysis (heating in the absence of oxygen) of biomass. Chars and charcoal-like materials occur naturally in soils and are considered part of the soil organic carbon pools (Skjemstad *et al.* 1996). High fertility associated with the anthropogenic soils, *terra preta*, in the Amazon has been related to the high content of organic carbon in the form of char and the practice of ‘slash and char’ by the pre-Columbian indigenous people of the Amazon (Glaser *et al.* 2001). Recently, there has been much interest in biochars, which is driven by 2 major global issues: climate change and the realisation of the need for more sustainable soil management. First, artificially produced biochar is a product of the renewable-energy-focused pyrolysis technology which produces biofuel to displace fossil fuel use. Apart from the carbon offset due to the production of biofuel, the relatively stable nature of biochar material also could have carbon sequestration value (Lehmann *et al.* 2006). Second, biochars can potentially be used as soil amendments for improving the quality of agricultural soils (Glaser *et al.* 2002a, 2002b; Lehmann *et al.* 2003). The long turnover time and therefore the inert nature of biochar has often been emphasised for this purpose.

As pointed out by Day *et al.* (2004), using biochar to sequester carbon in agricultural land as a way to combat climate change can only be accomplished economically if the sequestered C has

beneficial soil amendment and/or fertiliser values. Currently, very little biochar material is being used in agriculture in Australia and elsewhere. Therefore, in the future development of agricultural markets for biochars, agronomic values of these products in terms of crop response and soil health benefits need to be quantified. Beneficial effects of biochar in terms of increased crop yield and improved soil quality have been reported (e.g. Iswaran *et al.* 1980; Glaser *et al.* 2002a, 2002b). However, review of previous research showed a huge range of biochar application rates (0.5–135 t/ha of biochar) as well as a huge range of plant responses (–29–324%) (Glaser *et al.* 2002a). More importantly, in much of this research, properties of the biochar used in the investigation were not reported. Biochars can be produced from a range of organic materials and under different conditions resulting in products of varying properties (Baldock and Smernik 2002; Nguyen *et al.* 2004; Guerrero *et al.* 2005). Little research has been published elucidating the mechanisms responsible for the reported benefits of the biochars on crop growth, production, and soil quality. Such understanding is essential for development of agricultural markets for biochars and for the future development of technology for the production of biochar products with improved quality and value.

Greenwaste refers to the plant pruning and grass clippings collected from parks, gardens, and agricultural fields which have traditionally been disposed of by burning and landfilling.

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While conversion of these materials to compost has been a much-promoted option, currently only a very small amount of the products is being used in agriculture in Australia, e.g. only 4% of compost products is being used in agriculture in New South Wales due to various market barriers including high transport costs (Dorahy *et al.* 2005; Chan *et al.* 2007). Little is known of the agronomic value of biochar produced from greenwaste. In this paper, we report results of a research project designed to assess the agronomic value of biochar produced from greenwaste on plant yield and soil quality in a glasshouse pot experiment.

Materials and methods

Soil

The soil was collected from the Flat Paddock at the Centre for Recycled Organic in Agriculture (CROA) site, Menangle, near Camden (70 m AHD; 02883278E, 6224546N), NSW. The soil was an Alfisol (a Chromosol according to Australian Soil Classification; Isbell 1996). It is a typical agricultural soil of NSW and the site had a long history of cropping. The hardsetting A horizon had low soil organic carbon concentration and was acidic, with pH_{Ca} of 4.5 (Table 1). A composite sample was collected from the 0 to 0.1 m layer, brought back to the laboratory, and sieved through a 6-mm aperture sieve.

Biochar

The feedstock of biochar was greenwaste which was a mixture of grass clippings, cotton trash, and plant prunings. It was manufactured at a temperature of around 450°C in a low temperature pyrolysis plant by BEST Energies Australia. The temperature was chosen based on the recommendation of Day *et al.* (2004) on the manufacturing of biochar for soil amendment purposes. The biochar was alkaline in nature, high in total carbon but low in total nitrogen (1.3 g/kg), with C/N of 200 and extremely low in mineral nitrogen (<0.5 mg/kg) (Table 1).

Pot trial

The experiment was carried out in a temperature-controlled glasshouse (20–26°C). The experimental design used was factorial randomised block design with 5 replications. Four biochar rates (0, 10, 50, 100 t/ha) combined with 2 nitrogen fertiliser rates (0, 100 kg/ha) were used.

Air-dried soil and biochar-amended soils (1.25 kg oven-dried equivalent) were packed into black plastic cylindrical pots (14 cm i.d. by 14.5 cm tall) to achieve a bulk density of 1.2 Mg/m³. Nitrogen fertiliser (NH₄NO₃), in solution was

added in equivalent amounts to half of the pots. All the pots were then wetted up to field capacity using de-ionised water. Ten seeds of radish (*Raphanus sativus* var. Long Scarlet) were planted in each pot and thinned to 5 seedlings after emergence. The pots were placed in a shallow tray and regularly watered to maintain water content at approximately field capacity throughout the duration of the experiment. Radish was chosen for the pot trial because it is the indicator plant used for assessing composts, soil conditioners, and mulches (Standards Australia 2003).

Soil, biochar, and plant analyses

At the completion of the pot trial (6 weeks), the whole radish plants were harvested by removing them from the individual pots. The plants were washed with de-ionised water, and oven-dried at 70°C to constant weight before weighing to determine the dry matter production.

After harvesting, the soil from each pot was air-dried at 36°C, mixed thoroughly, and crushed gently to pass through a 4-mm sieve. A subsample was ground further to pass through a 2-mm sieve. The samples <2 mm were then analysed for pH, total carbon, total nitrogen, extractable phosphorus (Colwell), and exchangeable cations following Rayment and Higginson (1992); pH was measured in 1:5 soil/0.01 M CaCl₂ extract; total carbon and total nitrogen were measured by combustion method; extractable phosphorus was determined by Colwell method and exchangeable cations were determined using the Gillman and Sumpter method. Soil water content at field capacity (–10 kPa) and permanent wilting point (–1.5 MPa) were determined on <2 mm soil samples using tension plate and pressure plate techniques respectively. The fluorescein diacetate hydrolysis test (FDA test) for microbial activity (based on Schnurer and Rosswall 1982) was carried out on samples <2 mm after re-wetting and equilibrating the samples at field capacity soil water content. Hydrolysis of fluorescein diacetate was assayed using a modified method described by Zelles *et al.* (1991).

Soil tensile strength determination

Air-dried soil samples (<4 mm) collected after the pot trial from all the different biochar rates treatments (only nil N treatments) were quickly wetted by pouring into perspex soil cylinders (2.5 cm i.d. by 1.4 cm height), which were immersed in water in a shallow tray. After 4 h of equilibration, the soil cylinders were drained to remove free water and dried at 40°C to constant weight. The soil cylinders were then crushed between parallel plates to determine the crushing force. The tensile strength (T, in

Table 1. Basic chemical properties of the soil and biochar used in the pot trial experiment

EC (dS/m)	pH CaCl ₂	Colwell P	KCl-extract. ammonium-N (mg/kg)	KCl-extract. nitrate-N	N (g/kg)	C	Exchangeable cations					CEC
							Al	Ca	K	Mg	Na	
0.05	4.5	34	6.1	12	1.3	18	0.5	5.1	0.26	1.7	0.16	7.7
3.2	9.4	400	<0.30	<0.20	1.8	360	<0.1	0.4	21	0.56	2.4	24

kPa) of soil cylinder was calculated using the equation (Dexter and Kroesbergen 1985):

$$T = 2F \times 98.1/(\pi DL)$$

where F is crushing force (kg), D is diameter of soil cylinder (cm), and L is height of soil cylinder (cm). Each treatment was replicated 8 times.

The tensile strength determination is a soil strength measurement and was used here to compare the biochar treatments in term of their effect on soil hardsettingness (Mullins *et al.* 1990).

Statistical analyses

All data were analysed by 2-way analyses of variance using GENSTAT 9.1 (Lawes Agricultural Trust 2006). The treatment means were compared using least significant differences for the main effects of biochar and nitrogen fertiliser as well as their interactions. Unless otherwise stated, differences were significant at $P = 0.05$.

Results

Plant responses — dry matter production

In the absence of nitrogen fertiliser, application of biochar made from greenwaste did not increase the dry matter (DM) production of radish even at the highest rate (100 t/ha) (Fig. 1). Instead, at 10 t/ha of biochar, yield was slightly depressed compared with the nil biochar control. With the addition of nitrogen fertiliser (100 kg N/ha), significant increases in radish yield were observed in all the biochar treatments

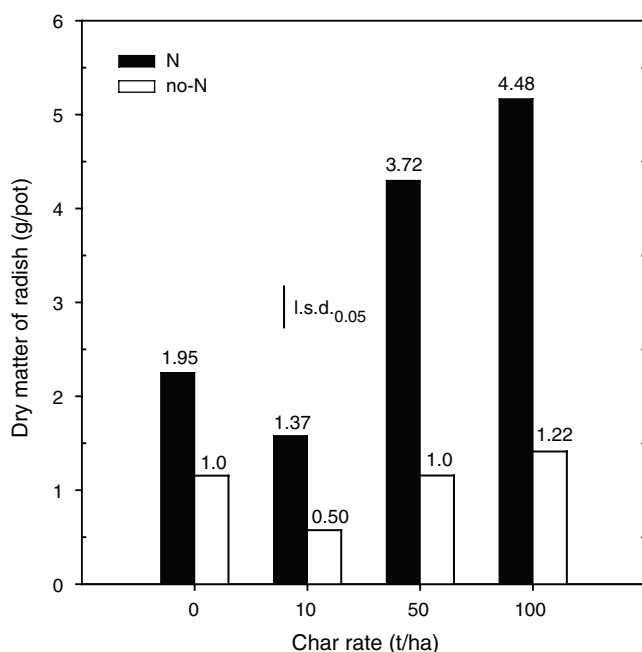


Fig. 1. Dry matter production of radish with and without nitrogen fertiliser as a function of rate of biochar. Numbers on top of bar refer to relative yield, i.e. DM of a treatment as a proportion of DM of the control (nil biochar and nil N).

(including the nil biochar control), and there was a significant interaction between biochar application rates and nitrogen fertiliser addition. The latter refers to the observation that the increases in DM of radish with nitrogen addition were much greater in the biochar-amended soils than the nil biochar control and that the magnitude of yield response increased with the application rate of biochar. For example, additional increase in DM of radish due to N fertiliser varied from 95% in the nil biochar control to 266% in the 100 t/ha biochar-amended soils (Fig. 1). Interestingly, the depression in yield at 10 t/ha of biochar was not eliminated by the addition of N fertiliser. When the DM results are expressed as relative yield (RY), namely DM of a treatment as a proportion of DM of the control (nil biochar and nil N), RY was 0.5 at 10 t/ha and did not increase significantly above 1.0 at higher rates of biochar application in the absence of N fertiliser (Fig. 1). With N fertiliser addition, RY of radish increased to 1.95 at nil rate of biochar and this increase could therefore be attributed to the N fertiliser alone. It has been estimated that for biochar rates >20 t/ha, RY exceeded 2.0 and finally increased to 4.5 at 100 t/ha of biochar (Fig. 1). Therefore, there was an additional yield increase as a result of increased biochar application for rates >20 t/ha which could not be solely attributed to the addition of N fertiliser.

Plant tissue analyses of radish revealed significantly higher nitrogen concentration as a result of N fertiliser application (mean of 6.27 v. 2.17%) (Table 2). Without N fertiliser, N content of radish remained <3% but this increased to >6% in the presence of N fertiliser. This and the marked DM responses of radish plants to N fertiliser (95% increase in DM at nil biochar treatment) (Fig. 1) indicated that the soil was limiting in N. Given the low N content (1.3 g/kg), negligible mineral N, and high C/N ratio (200) of the biochar used in this investigation (Table 1), its addition to soil did not provide any additional available nitrogen to the radish plants, and therefore did not result in yield increase even at the rate of 100 t/ha. This is further confirmed by the results for N uptake by radish, in that N uptake remained low and unchanged at different biochar rates in the absence of N fertiliser but increased markedly as a result of N fertiliser application (Table 3). Biochar application increased P, K, and Ca but not Mg concentration of the radish plants and significant increases were found only at the higher application rates of 50 and 100 t/ha (when no N was applied) (Table 2). The increase in P and K contents of the radish plants growing in biochar-amended soil was related to the high concentrations of available P and exchangeable K present in the greenwaste biochar (Table 1). As N is principally taken up as NO_3^- and is a dominant nutrient, its uptake has to be balanced by cations to maintain electrical neutrality. From nutrient uptake data (Table 3), increasing N uptake at higher biochar rates was accompanied by increased K and to a lesser extent Ca uptake, it is therefore clear that K was the dominant counter cation. The lower P concentration of the radish plants found in the presence of N fertiliser (compared with nil N fertiliser) (Table 2) was a dilution effect due to the larger DM production. This is confirmed by the P uptake results which indicated higher uptake at higher biochar rates in the presence of N fertiliser. Mg concentration of the radish plants was fairly similar at all different rates of biochar application but a slight reduction was detected at 10 t/ha in the absence of N and at 50 t/ha in the presence of N fertiliser (Table 2).

Table 2. Nutrient concentration (%) of radish plants grown in biochar-amended soils at different rates and with and without N fertiliser
Within rows, means followed by the same letter are not significantly different ($P > 0.05$); n.s., not significant ($P > 0.05$); * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

Biochar rate:	Nil N				N				Significance level		
	0	10	50	100	0	10	50	100	Biochar rate	N	Biochar $\times$ N
				(t/ha)							
N	2.11c	2.78b	1.85c	1.94c	6.66a	6.23a	6.08a	6.08a	**	***	***
P	0.25d	0.24d	0.53b	0.62a	0.16e	0.16e	0.21d	0.31c	***	***	***
K	2.67d	2.44de	3.40c	3.75bc	2.17e	2.62d	3.86b	5.88a	***	***	***
Ca	1.32c	1.26c	1.59b	1.61ab	1.50b	1.63ab	1.38c	1.72a	*	**	**
Mg	0.32b	0.28c	0.35ab	0.36ab	0.37a	0.39a	0.32b	0.37a	n.s.	*	***

Table 3. Uptake of nutrients (g) by radish plants grown in biochar-amended soils at different rates and with and without N fertiliser
Within rows, means followed by the same letter are not significantly different ($P > 0.05$); *** $P < 0.001$

Biochar rate:	Nil N				N				Significance level		
	0	10	50	100	0	10	50	100	Biochar rate	N	Biochar $\times$ N
				(t/ha)							
N	0.024e	0.015e	0.021e	0.027e	0.151c	0.098d	0.263b	0.323a	***	***	***
P	0.003de	0.002e	0.006c	0.009b	0.004d	0.002e	0.009b	0.016a	***	***	***
K	0.031cd	0.013d	0.039cd	0.052c	0.050c	0.041cd	0.168b	0.301a	***	***	***
Ca	0.015de	0.007e	0.019d	0.023d	0.033c	0.025d	0.059b	0.088a	***	***	***
Mg	0.004e	0.002f	0.004e	0.005cd	0.008c	0.006d	0.014b	0.019a	***	***	***

Soil quality changes

Changes in a range of soil chemical properties as a result of different rates of biochar application, as measured at the end of the pot experiment, are presented in Table 4. The changes included increases in pH, organic carbon, and exchangeable Na, K, and Ca as well as extractable P but decreases in exchangeable Al. The magnitude of changes was roughly proportional to the rate of biochar application (e.g. increases with increasing rate of biochar application). In many cases, statistical difference was detectable only in the higher rates, namely 50 and 100 t/ha of biochar application but not at 10 t/ha (Table 4). The pH increased by 1.22 (4.77 v. 5.99) between the nil char and 100 t/ha char treatment in the absence of N fertiliser and the

corresponding increase was 0.61 unit in the presence of N fertiliser. The pH increases were accompanied by significant reduction in exchangeable Al by >50% at the higher rates of biochar application, i.e. 50 and 100 t/ha (Table 4).

Tensile strength of the hardsetting soil under investigation decreased with increasing rate of biochar application (Table 5). However, no significant change was detectable at the low rate of 10 t/ha and significant reduction was only observed at 50 and 100 t/ha of biochar application. Field capacity of the biochar-amended soil increased with increasing rate of biochar application but significant increases were detected only at the higher rates of 50 and 100 t/ha of biochar (Table 5). Biochar application also had significant effect on soil biological activities

Table 4. Changes in soil chemical properties as a result of different rates of biochar application with and without nitrogen fertiliser application
Within rows, means followed by the same letter are not significantly different ($P > 0.05$); n.s., not significant ($P > 0.05$); * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

Biochar rate:	Nil N				N				Significance level		
	0	10	50	100	0	10	50	100	Biochar rate	N	Biochar $\times$ N
				(t/ha)							
pH _{ca}	4.77c	4.75c	5.38b	5.99a	4.58c	4.61c	4.75c	5.19b	***	***	***
C (g/kg)	21.6c	27.0c	43.4b	64.6a	21.2c	23.0c	42.4b	64.6a	***	n.s.	n.s.
Total N (g/kg)	1.7a	1.4a	1.5a	1.6a	—	—	—	—	n.s.	—	—
Ex. Na (cmol/kg)	0.60b	0.58b	0.74a	0.84a	0.48c	0.46c	0.60a	0.69b	***	***	n.s.
Ex. K (cmol/kg)	0.24f	0.40e	0.92c	1.60a	0.21f	0.39e	0.56d	1.30b	***	***	***
Ex. Ca (cmol/kg)	5.50b	5.18b	5.58b	6.30a	5.40b	5.28b	5.68b	6.20a	***	n.s.	n.s.
Ex Mg (cmol/kg)	1.84a	1.70b	1.86a	1.88a	1.80a	1.56b	1.76a	1.86a	**	***	n.s.
Ex Al (cmol/kg)	0.25a	0.23a	0.10b	0.10b	0.27a	0.29a	0.12b	0.10b	***	**	n.s.
eCEC (cmol/kg)	8.42c	8.08c	9.10b	10.60a	8.18c	7.96c	8.68b	9.94a	***	***	n.s.
Colwell P (mg/kg)	23.8c	26.6c	32.6b	40.8a	28.6c	24.6c	29.6b	40.8a	***	n.s.	*

Table 5. Changes in soil physical and biological properties as a result of different rates of biochar application with and without nitrogen fertiliser applicationWithin rows, means followed by the same letter are not significantly different ($P > 0.05$); n.s., not significant ($P > 0.05$); *** $P < 0.001$. NA, not available

Biochar rate:	Nil N				N				Significance		
	0	10	50	100	0	10	50	100	Biochar rate	N	Biochar $\times$ N
	(t/ha)										
FC (kg/100 kg)	0.255c	0.244c	0.270b	0.320a	0.252c	0.246c	0.270b	0.320a	***	n.s.	n.s.
Tensile strength (kPa)	64.4a	69.2a	31.7b	18.8c	NA	NA	NA	NA	***	—	—
FDA(μ g fluorescein/g soil.min)	13.2a	11.3b	11.9b	11.5b	10.1c	8.6d	11.2b	11.2b	***	***	***

as indicated by FDA enzymatic test. The FDA test is a measure of microbiological activity based on enzymatic activities (Schnurer and Rosswall 1982). The highest microbial activity (highest FDA hydrolysed) was found in the nil biochar nil N soil. In the absence of N fertiliser, FDA hydrolysed was higher in the nil biochar soil. However, the reverse was true when N was applied, in that FDA was higher in the biochar-amended soils than the nil biochar control soil, with the exception of the 10 t/ha treatment, which had the lowest FDA of all treatments (Table 5).

Discussion

Agronomic value of greenwaste biochar

Biochar application did not increase radish dry matter yield even at the highest rate of application (100 t/ha). Given the low N content and high C/N (200) of the biochar, growth of radish in the biochar-amended soil alone was likely to be limited by N supply. This was confirmed by the large yield increase (95%) observed when N fertiliser was applied in the nil char treatment. The additional increases in radish yield observed at higher rates of biochar applications (50 and 100 t/ha) in the presence of N fertiliser (up to 266% in the case of 100 t/ha biochar application) indicated the potential of greenwaste biochar in increasing nitrogen fertiliser use efficiency of plants. This might be a consequence of the various improvements in soil quality detected in the biochar-amended soils. Particularly significant are the improvements in soil physical conditions of the soil, namely reduction in tensile strength and higher field capacity water content. Both improved the physical soil environment of this hardsetting soil (Mullins *et al.* 1990), rendering it a more favourable root growth environment and therefore increasing the ability of the plants to utilise the applied N, with the resulting increases in DM. The increases in pH and the corresponding reduction in exchangeable Al (Table 4) could also have improved the chemical environment of the biochar-amended soils for the radish plants. Furthermore, the increased DM of radish at higher biochar rates could partly be attributed to the increased supply of P and K in the biochar-amended soils when N was no longer limiting (i.e. in the presence of N fertiliser). The biochar used in the investigation was high in both of these nutrients (Table 1). From the pot trial results, we cannot identify the reason(s) for the negative yield observed at 10 t/ha of biochar application. However, it is interesting to point out that most of the positive changes in soil quality reported for the higher rates of biochar application, e.g. reduction in tensile strength, were not detectable at this low rate. Negative plant responses due to biochar application have been previously reported (Mikan and

Abrams 1995) and further research is needed to identify the cause(s).

Improvement in soil quality

Results highlight the potential effectiveness of the greenwaste biochar as a soil conditioner for the hardsetting soil. The changes in soil properties, such as increases in organic carbon and pH and reduction in soil strength were consistent with the properties of the greenwaste biochar used in this investigation, which was alkaline and high in carbon content. The apparent contradictory effect of biochar on soil microbiological activities as indicated by the FDA test in the absence compared to the presence of N fertiliser could be related to short-term nature of the pot trial conditions and requires further research.

Hardsetting soils are very widespread in Australia, and it has been estimated there are around 100 Mha (Mullins *et al.* 1990), covering many of the agriculturally important soils, e.g. Chromosols, Sodosols. They are characterised by their fragile soil structural conditions and associated physical limitations to agriculture. Under cropping, SOC is often low, ~1%, and nitrogen fertiliser is a major input for crop production in these soils. Our results therefore highlight the potential benefits of biochar application in improving the quality of these soils, particularly in increasing the N fertiliser use efficiency of these soils. However, given the short-term nature of the pot trial, further research in field trials is needed to fully quantify the long-term benefits of using this biochar as soil amendment. Of particular interest is the stability of the carbon in the biochar in soil environment and hence the long-term soil carbon sequestration value. Field experiments are also needed to allow hypotheses to be tested that cannot be addressed under pot trial conditions. These include effects of biochar on soil biology, nutrient leaching/retention, and long-term soil structural changes. Some of the changes to biochar when applied to soils could have long-term significance to biogeochemical processes in soils, e.g. increases in cation exchange capacity in relation to nutrient cycling (Liang *et al.* 2006).

Conclusions

Application of greenwaste biochar alone to a hardsetting soil did not result in significant increases in radish dry matter yield, even at the highest rate of application (100 t/ha). However, significantly yield increases additional to that due to N fertiliser were observed when biochar was applied together with the fertiliser, therefore highlighting the role of biochar in improving N fertiliser use efficiency. Our pot experiment results also

indicated significant changes in soil quality including increases in pH, organic carbon, and exchangeable cations as well as reduction in tensile strength at higher rates of biochar application (>50 t/ha) but field experiments are needed to confirm and quantify the long-term benefits.

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